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# Rising Total Cross Section and Large Transverse Momentum Phenomena, Two Topical Questions at Very High Energies*

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## I. INTRODUCTION

This paper is meant as an introduction to a Particle and Fields session on Strong Interactions Physics, where new results from NAL are presented.[1] It is however not attempted to quickly review the pertinent topical themes of this whole domain of particle physics as they now look before all the new pieces of information to be discussed later in this session are properly assimilated. I have rather decided to limit myself from the start to only two of these topics, namely the question of the rising proton proton cross section and the question of large transverse momentum phenomena, respectively.[2] In both cases, a relatively large amount of information could already be collected at the ISR and at NAL, since these two questions separately originated from ISR experiments, completed slightly over one year ago.[3] A lot more can rightfully be expected in the near future. The first results have indeed quickly triggered several experimental proposals some of which have already worked their way up to the data taking stage.[4] At present, it is already possible in both cases to stress a few important properties which altogether provide a relatively clear phenomenological definition of the observed effects. In both cases however it is yet too early to say much about the underlaying dynamics. Quite different models can still adjust themselves to the limited amount of data which is now available. This is in turn what may make these two topics worth another general discussion.[3,5] The purpose of this paper is to bring into focus a few key properties already ascertained. This will make obvious the present complementarity between information coming from the CERN-ISR and from NAL. The questions at stake appear as of great importance. We may hope that their detailed understanding will not be a deception in that respect.

## II. THE PROTON PROTON TOTAL CROSS SECTION

Figure 1, which provides a compilation of total cross section data has by now become familiar. The expert may notice a few normalization shifts at the one percent level.[6] There are also two new counter points from NAL.[7] The well known 10% rise over the ISR energy range stands as a prominent fact. The ISR points correspond to the by now standard choices of beam momentum, namely 11, 15, 22, 26 and 31 GeV/c, respectively. Runs with different momenta for the two stored beams (Pisa-Stony Brook) have given values at intermediate energies.[6] This only confirms the energy dependence well enough displayed already in Fig. 1. Measurements at the ISR combine global counting (Pisa-Stony Brook), with $\sigma$ being obtained from the observed counting rate as inversely proportional to the machine luminosity L, together with optical point measurements (CERN-Rome) which obtain $\sigma$ from the forward differential rate, as inversely proportional to $\sqrt{L}$. In the lower part of the ISR energy range

($\sqrt{S}<30$GeV), normalization to Coulomb scattering is also possible. One thus confirms results obtained using the separately measured value of L as an intermediate step. One may of course use the different dependence on $\sigma$ of the two rates actually measured in the Pisa Stony Brook and CERN-Rome experiments, to obtain both $\sigma$ and L independently of any direct luminosity measurement. This has been done and gives perfectly consistent results.[8] Nevertheless, one had so far to make do with the fact that the two experiments collected data on different intersections and at different times. The two groups will run together, with both techniques being used, at the same time, and on the same intersection. This, together with further beam profile measurements, should resolve any question which one may still consider with respect to the uncertainties attached to the luminosity. It should in any case allow to improve on the errors appearing in Fig. 1 and in Fig. 2. This is part of the further study of $\sigma$ to be carried out now at the ISR. At the same time, the Aachen-CERN-Genova-Harvard-Torino collaboration is starting a new measurement of the differential cross section.[9] This should provide a new and independent optical point determination of $\sigma$.

It is not yet possible to associate rising cross sections with any specific dynamical mechanism. Quite different models can be proposed.[3] More generally speaking it may be the onset of an asymptotic trend or a slow transition to an eventually constant value.[5,10]

Results from NAL on total cross sections for different channels at energies up to 400 GeV should be more helpful than the relative merits of different parametrizations of the ISR results in trying to find necessary clues.[11] At present, cosmic ray results cannot help much the choice.[12] Focusing on proton proton interactions alone, one may however exploit the fact that the energy behaviour of the total cross section has related effects on elastic scattering which, at these energies, is essentially the shadow of inelastic processes. This should provide at least cross checks and some insight. Two parameters practically characterize low momentum transfer elastic scattering. The first one is the slope parameter b of the differential cross section. At low absolute values of the momentum transfer squared t $\left( |t| < 0.1 (\mathrm{GeV}/c)^2 \right)$, the differential cross section can indeed be parametrized as $d\sigma/dt = (d\sigma/dt)_{t=0} e^{bt}$. The second one is the ratio of the real to the imaginary part of the forward scattering amplitude, $\rho$. It is the study of the energy behaviour of these parameters, and in particular over the NAL energy range,[13] which actually constitutes the new important pieces of information under the general heading of total cross sections.

Unitarity puts a constraint on the combined behaviour of $\sigma$ and b.[14] In particular if $\sigma$ rises assymptotically, then so must b. Figure 2 gives a compilation of the values of b, as now obtained through the Serpukhov, NAL and ISR energy ranges. The slope parameter increases with energy as one should rightfully expect from diffraction from an object the size of which increases. Nevertheless the rise of $\sigma$ and the rise of b are not both amenable to the same simple type of parametrization over such a wide energy interval. The diffraction peaks shrinks but not as rapidly as one could expect it to from the increase of $\sigma$, if it were due to an increase in size at maximum opacity. This is perfectly allowed and simple parametrization for the increase of $\sigma$ and b, of the $\log^2 s$ and $\log s$ type respectively, would, even if naively extrapolated, do not conflict with unitarity before one has reached extremely high energies.[5,14] Furthermore on any relatively restricted energy range (NAL or ISR) the rises of $\sigma$ and of b are quite compatible.[15] It is only when perused on a very wide energy interval that the behaviours of $\sigma$ and of b suggest an object which increases in size (larger values of the impact parameter becomes relevant) and opacity (Absorption still increases at intermediate values of the impact parameter). However, as now discussed, the overall increase in opacity still leads us far below what the full absorption limit would give.[16] Associating elastic scattering with a purely shadow effect,[17] one may consider the differential elastic cross section as the Fourier-Bessel transform of an imaginary scattering amplitude at fixed impact parameter r. This imaginary amplitude readily gives the inelastic cross section (or the opacity) for r. One may thus obtain the variation of the inelastic differential cross section. The conclusion is that the rise of the cross section is mainly confined to the peripheral zone $\left(r \geq 10^{-13} \text{cm}\right)$ and relatively small as compared to what it could be were the proton to become completely opaque. This has been particularily emphasized by U. Amaldi[5] and studied in detail in several recent papers.[18] The elastic differential cross section is written as

$$\frac{d\sigma}{dt} = \pi \left| \int_0^\infty f(r)\ J_0(r\sqrt{-t})\ r\,dr \right|^2 \tag{1}$$

$$\text{with} \quad f(r) = 1 - \sqrt{1-\sigma_{in}(r)}\ . \tag{2}$$

This neglects a possible real part as well as spin effects. The inelastic cross section is then given by $\sigma_{in} = \int \sigma_{in}(r)\, d^2r$. For an imaginary amplitude, $\left[1-\sigma_{in}(r)\right]^{1/2}$ is the inelasticity parameter. One may then obtain the variation of the inelastic cross section as a function of energy for different values of the impact parameter $r$, or the variation of the proton opacity. Using (1) and (2) this is readily calculated from the variation of the elastic differential cross section. The behaviour of $\frac{d\sigma_{in}}{dr} = 2\pi r \sigma_{in}(r)$ as a function of $r$, at two different energies is shown in Fig. 3. Also given is the variation of the difference between the two values as a function of $r$. One sees that the rise of the inelastic cross section is much more peripheral than the overall absorption itself. Furthermore it is extremely small as compared to what the black disc limit would allow. This is a fact which any model for the rising cross section has to acknowledge.

The energy behaviour of $\rho$ should also reflect the rise of the total cross section. Any rising logarithmic term in $\sigma$, which one may infer from Fig. 1, whether it is associated with an eikonal approach (Foissart bound) or expected from a decreasing cut contribution (Reggeon calculus), implies a positive value for $\rho$ which eventually decreases with energy as $(\log S)^{-1}$. This actually assumes that the scattering amplitude is asymptotically even under crossing symmetry.[19] The imaginary part of the amplitude should be dominantly even and is expected to become even asymptotically.[20] The real part turns out to be asymptotically even in all "reasonable" models so far considered.[21] From analyticity and crossing symmetry one may write for an even (odd) amplitude

$$F^{*}(S) = \pm e^{i\pi \frac{\partial}{\partial \log S}} F(S) \tag{3}$$

One thus exploits the analyticity property in the s (log S) plane, continuing from the upper side of the right hand cut to the upper side of the left hand cut. It easily follows from (3) (with the positive sign) that a positive derivative of the cross section with respect to log S implies a positive value for $\rho$ which decreases as $(\log S)^{-1}$. One may perhaps more simply write $(\log S - \frac{i\pi}{2})$ instead of "log S" whenever it appears in any guessed at expression of the scattering amplitude. This is required if one wishes to have an amplitude which would be even under crossing.

This result is particularly interesting in view of the fact that, up to Serpukhov energies, $\rho$ was known to be <u>negative</u> and decreasing in absolute value. A rising cross section then implies that $\rho$ has to vanish.[21] Dispersion calculations[22] predicted that it would then occur within the NAL Energy range. This was indeed compatible with ISR measurements giving a value compatible with zero (Fig. 4). The important new development is the precise measurement of $\rho$ over the NAL energy range.[13] This shows that $\rho$ indeed vanishes. A compilation of available data on $\rho$ is given in Fig. 4. The vanishing of $\rho$ can rightfully be considered as an indirect confirmation of the rising cross section. The behaviour of $\rho$ does not exactly imply a rising cross section. However, if it were not the case, one would have to see a very peculiar behaviour of $\sigma_{p\bar{p}}$ (surprising 0∂∂ term). This may be considered as unlikely. $\sigma_{p\bar{p}}$ should in any case soon be measured at NAL.

If duality calls for some cancellations among Reggeon contributions to the imaginary part, it is not so for the real part.[23] The behaviour of $\rho$ implies compensating effects between a positive and slowly decreasing diffractive term and a negative and rapidly decreasing Regge term. The same analysis is readily extended to $p\bar{p}$ scattering and one finds that the real part of the $p\bar{p}$ amplitude should be found positive at much lower energies than that necessary for the pp amplitude. Again one here assumes that the $p\bar{p}$ cross section does not show any very peculiar behaviour. $\sigma_{p\bar{p}}$ should then pass through a marked minimum within the NAL energy range. Does it?

The list of data which we may eagerly wait for is already long. One should mention that measurements of $\rho$ at higher ISR energy would be very useful. It is generally expected that $\rho$ will reach its maximum around 2000 GeV and then slowly decrease. How big this maximum is (0.1?) should help differentiate between models. It should also be stressed that better values for b should also be very useful. In particular the precise energy behaviour of $\sigma_{el}/\sigma$ would be very interesting. It is improbable that it stays exactly the same.[8] The eikonal approach would certainly favor a rising $\sigma_{el}/\sigma$ while the Reggeon calculus approach would obviously favor a decreasing $\sigma_{el}/\sigma$. As the variation of $\sigma$ and b, the effect is however expected to require a rather large energy interval if it is to be easily seen.[24,25]

## III. <u>LARGE TRANSVERSE MOMENTUM PHENOMENA</u>

It is well known that most of the secondary particles produced in high energy collisions are pions with small transverse momentum ($\langle p_T \rangle = 0.35$ GeV/c). The populated region in phase space is practically linear, with a transverse momentum distribution well reproduced by an exponential, viz.,

$$\frac{d\sigma}{dp_T^{\,2}} = A\, e^{-Bp_T} \quad (0.1 < p_T < 1\mathrm{GeV}/c) \tag{4}$$

with $B = 6\ \mathrm{GeV}^{-1}$

This actually refers more specifically to particles produced at wide angles in the center of mass system or, in other words, at $x$ values (the Feynman scaling variable) in the neighborhood of zero.[2] One could expect however that, if only for the presence of electromagnetic interactions, such an exponential behaviour could not continue too far in $p_T$. By $p_T$ = 5GeV/c or so, electromagnetic production, with a much more gentle $p_T$ fall off should have become competitive with an exponentially decrease hadronic component.[26] Furthermore, the scaling property of the electromagnetic strength function, together with the fact that hadron hadron scattering at fixed wide angles appears to fall with energy as an inverse power rather than an exponential, lead to expect that strong interactions also could produce secondaries with kinematical configurations similar to those expected from electromagnetic interactions, but then with a much higher yield.[5,27,28] The exponential behaviour found at low $p_T$ ($p_T$ < 1GeV/c) was then not expected to hold on beyond 2 GeV/c. Experimental evidence for such an effect came at the time of the Batavia Conference.[3,29] Figure 5, which puts together some of the data obtained by the Saclay-Strasbourg collaboration[3] illustrates three important points. A witness of the power and limitation of present day wide angle spectrometers, it combines the inclusive positive yield up to $p_T = 3$ GeV/c with the inclusive pion yield at larger $p_T$. These data correspond to $\sqrt{S} = 53$ GeV. Also shown is the energy dependence of the integrated pion yield at large $p_T$ ($3 < p_T < 5$ GeV/c)

i) One notices right away that the observed rates at large $p_T$ are considerably higher than what one could naively expect from the exponential behaviour followed by the low $p_T$ data.

ii) One also sees that, as one reaches large $p_T$ values, the pions have lost the overwhelming majority which they have at low $p_T$ and, therefore, in general. At the same time other data show that the positive yield, which is within errors, compatible with the negative one at low $p_T$, becomes definitely larger than one (1.4 say).

iii) One also notices a strong energy dependence of the integrated pion yield at large $p_T$. It rises by an order of magnitude over the ISR energy range. This is to be contrasted with the behaviour of the low $p_T$ yield ($p_T = 0.3$ GeV/c say) which rises by 10% or so only.

The first and third features are very well illustrated by Fig. 6 which shows the large $p_T$ distribution for $\pi^0$ observed by the CERN-Columbia-Rockefeller collaboration.[3, 30, 31] One also notices the departure from the exponential behaviour and the prominent increase with energy of the measured rates at large $p_T$, and the more so, the larger $p_T$ is. The explored $p_T$ range is large enough that an inverse power can definitely be preferred over an exponential. A simple and satisfactory fit can be provided by $p_T^{-8}$. This does not of course exclude other choices.

The same features have been observed in inclusive distributions measured at NAL for $\pi^0$ [32] and more extensively for charged particles.[33] In the latter case the $p_T$ range explored at 200 and 300 GeV [34] extends from 1 to 7 GeV/c.

We now come back to the second point, stressed in connection with Fig. 5. At present some detailed results from ISR and NAL can be perused, as typical of the observed effect. Figure 7-a shows the relative amount of "stable" charged particles as a function of $p_T$. The data are from the British-Scandinavian collaboration.[3,35] One sees that, as $p_T$ increases, the relative amount of pions quickly drops as the relative amount of heavy particles rises accordingly.[36] It is however remarkable that, beyond 1 GeV/c, the relative rates stabilize over a relatively wide $p_T$ range. The pions barely keep a majority which was overwhelming (85%) at low $p_T$. Figure 7-b gives in a complementary way the $\pi^+/\pi^-$, $p/\bar{p}$ and $p/\pi^+$ ratios which are measured over the same $p_T$ range. The $k^+/k^-$ ratio is very close to the $\pi^+/\pi^-$ one. This altogether corresponds to an excess of positives over negatives.

It is however not only due to the importance of the proton component when the anti-proton rates are still not very large. The $\pi^+/\pi^-$ is larger than what it is at low values of $p_T$. The stability of these ratios over a large $p_T$ range can be contrasted to their rapid variation below 1 GeV/c. This qualitatively defines a large $p_T$ regime. It suggests that production of large $p_T$ secondaries ($p_T$ = 3 GeV/c say) proceeds through mechanisms which may be different from those responsible for most of what is happening. To the extent that production at large $p_T$ reflects behaviour at small distances in a direction unaltered by the Lorentz contraction, this is particularily interesting. Results from NAL confirm the stability of the particle ratio found at the ISR.[33, 34] This is shown in Fig. 7-c which combines ratios observed at 300 GeV/c with data from the British Scandinavian collaboration at the same center of mass energy. The $\bar{p}$ behaviour at large $p_T$ notwithstanding, the relatively small variations of the relative yields are impressive. Results shown in Fig. 7 are both important and a plea for more data. The British Scandinavian collaboration goes up to $p_T \approx 3$ GeV/c at $\sqrt{S}$ = 53 GeV only. When it could overlap in energy with the Chicago-Princeton group it does not overlap in transverse momentum. We may hope for more data soon. This is the more so interesting that the $p/\pi^+$ ratio at $p_T$ = 3 GeV/c say, appears to fall with energy. It drops by a factor 3 when the center of mass energy doubles (Fig. 7-b and 7-c). It suffers already significant drops between 200 and 300 and 300 and 400. Whether it appears to go to a limit or not with increasing energy is a very interesting question.[37] Protons observed at wide angles could have different dynamical origins with different specific energy dependence.[38] One should always keep in mind that one is dealing with a small effect cross section wise and therefore that several a priori unlikely processes can be called upon to interpret the observed effects.

At present we may expect new data at wide angles with much overlap between CERN and NAL results. Normalization discrepancies are still around, even among different ISR results. They should be resolved with time. It seems more important to stress that all experiments agree on the key qualitative features of the data which we have itemized.

It should also be stressed that nothing very special should a priori distinguish $x = 0$ if these distributions actually probe the inner structure of the proton. It is a pity that practically all available data at $p_T \approx 3$ GeV/c are at wide angles. Results from the British-Scandinavian collaboration give inclusive positive and negative distributions which do not show any significant difference between 90° and 60°,[35] or say over two units of rapidity in the central region. This still corresponds however to $x \approx 0$. Data at smaller production angles in the center of mass would be very interesting to have. This is even more the case as soon as one discusses correlations. Dependence of particle ratios on the nature of the incident particles would also be very interesting and the more so that the observed positive excess may suggest a hard scattering between particle constituents.

In ISR experiments $p_T$ distributions are measured only far away from the phase space boundary; $p_T << \frac{\sqrt{S}}{2}$. The NAL experiment goes much closer to it. However target effects might then become of some importance. Whether a dull phase space cut off or something new happens is also an exciting question.

It is impossible to discuss here in any comprehensive way present theoretical approaches to large $p_T$ phenomena.[39] The relatively weak $p_T$ dependence of the inclusive distribution (inverse power as opposed to exponential), together with the prominent charge effects previously stressed are strong hints at drawing a parallel with deep inelastic electron scattering and its point like interaction interpretation. Large $p_T$ phenomena would then correspond to hard scattering between two proton constituents. This is the approach which we will follow, keeping in mind that, in view of the smallness of the cross section, many so called "possibilities" remain open.[39] It is then common practice to introduce factorization properties which allow a simple connection between the observed yield and the values of the strength functions measured in deep inelastic electron scattering.[3,27,28] The inclusive distribution which is then associated with full scaling properties reads[27,40]

$$E\frac{d\sigma}{d3p} \sim \frac{1}{{p_T}^4} F\left(\frac{2p_T}{\sqrt{S}}, y\right) \tag{5}$$

This would hold at values of $\sqrt{S}$ and $p_T$ much larger than all particle mass involved. F is further expected to approach a finite limiting value as S goes to infinity at fixed $p_T$. As a result, the inclusive distribution should eventually scale in the Feynman sense, but the more slowly with increasing energy, the larger $p_T$ is. A departure from an asymptotic $p_T^{-4}$ behaviour calls for specific mass parameters. This may however occur if more sophistication is introduced in a parton model which one may consider as a possible rationale for (5). One may for instance specify the amplitude for the scattered parton to result into one single large $p_T$ pion. The mass parameter would then be that associated with the pion form factor interpreted in the same way.[41] This is in turn compensated by extra powers of $p_T^2$ in the inclusive distribution. The generally expected behaviour is then of the type[3, 39]

$$E\frac{d\sigma}{d3p} \sim \frac{1}{p_T^N}\, G\left(\frac{2p_T}{\sqrt{S}}, y\right) \quad . \tag{6}$$

At present it is remarkable that the inclusive $\pi°$ distribution of the CERN-Columbia-Rockefeller collaboration[31] is indeed compatible with such a behaviour. Figure 8 gives a distribution of $p_T^N\ E\frac{d\sigma}{d3p}$ (with N = 8.26 as a best fit to the data) as a function of $x_T = \frac{2p_T}{\sqrt{S}}$, at $y \approx 0$. All data points are compatible with an asymptotic limit with the scaling property implied by (6). One may not yet conclude that the data practically impose such a behaviour. They however follow it in a remarkable way! N = 8 is furthermore expected for single hard $\pi^\circ$ scattering[41], with the pion form factor providing an extra $p_T^{-4}$ term in the expected rate.

Even if one keeps a $p_T^{-4}$ behaviour, associated with uncontrived jets of secondaries originating from a hard parton scattering as the eventual behaviour, it could be that the type of triggering used favors the observation of one single pion when a large transverse momentum particle is required. One may then expect that the observed reactions would essentially show a large $p_T$ $\pi^\circ$ on one side, with probably few associated soft pions on the same side, and some uncontrived jet of secondaries on the other side. Such a picture is not in disagreement with present data on correlations. However, before we turn to them, it is important to keep in mind that it would be extremely important to have more extended tests of (6). The charged pion data of the Chicago-Princeton collaboration could also follow such a behaviour but with a definitely larger value of N ($N \approx 11$).[42] It could be too poor an approximation to use (6) with relatively low values of $x_T$, as it is the case in Fig. 8. This question is obviously worth more attention.[43]

The charged multiplicity associated to a large transverse momentum $\pi^\circ$ has been measured by the CERN-Columbia Rockefeller collaboration using chambers covering two limited solid angle around 90°, in the direction of the observed $\pi^\circ$ and opposite to it, respectively. The results are shown in Fig. 9-a.[31] On the same side, the associated multiplicity increases practically linearly with $p_T$. On the same side it does not. Nevertheless it is larger than what expected on the average and the observed positive correlations are at least as large as what seen among wide angle secondaries.[2] Observing a wide angle large $p_T$ secondary is therefore a bias in favor of a large associated multiplicity at wide angles, not only in the opposite direction ($p_T$ has to be balanced) but also in the same direction. More detailed results have been obtained by the Pisa-Stony Brook Collaboration.[44] Positive correlations on the same side are found to be important and practically localized within two units of rapidity, in much the same way as those found among usual soft secondaries.[2] They do not change appreciably when $p_T$ varies between 0 and 4 GeV/c. Correlations on the opposite side are also positive, rather well localized in rapidity and increase with $p_T$. They are also relatively well localized angular wise as shown in Fig. 9-b, which gives the azimuthal distribution of the charged secondaries observed in coincidence with a $\pi^\circ$ with different $p_T$ values. This is suggestive of a jet, coplanar with the observed $\pi^\circ$ and the incident beam direction, though of a relatively fuzzy one. With a 4 GeV/c trigger, such correlations imply an excess of 4 or so extra charged particles in the opposite hemisphere from what one observes on the average. This is a sizeable increase of the multiplicity at wide angles and the more so that positive correlations are also present on the same side. This is however associated with a drop of the multiplicity at large longitudinal momenta. The average value of the transverse momentum carried by the particles seen in the opposite direction is much larger than the mean value of 0.35 GeV/c. How the overall momentum is actually shared among these particles is a very interesting question. The relatively wide opening of the jet (Fig. 9-b) suggests that many of the secondaries have rather small values of $p_T$, a very few only carrying large values of $p_T$. This last point is also supported by the important correlations observed among two large $p_T$ $\pi^\circ$ with opposite directions, as seen by the CERN-Columbia-Rockefeller collaboration. Increasing the required value of $p_T$ would then correspond to an important increase of the number of rather soft secondaries seen in the opposite direction together with a significant increase of the probability of finding hard ones. The detailed study of the nature and momenta of the associated secondaries has to wait for more involved experimental exploration than what has been so far possible.[4,5] The tentative picture just drawn can however already be helpful at further analyzing such reactions.[46]

It is obvious that it would be extremely important to know how $p_T$ is actually balanced. Whether it is balanced somewhat locally in rapidity, as expected when one also associates large $p_T$ secondaries to the (improbable) decay of clusters[2,3] or whether p is altogether balanced as expected from hard collisions between proton constituents. Correlations among particles with particular quantum numbers ($K^+$ and $K^-$ for instance) would also be very useful at distinguishing between models. At present, it is not possible to conclude that one is thus observing hard wide angle scattering between proton constituants. Nevertheless none of the observed effects contradict it while many of them do suggest a parallel with deep inelastic electron scattering. One should of course not undermine the problems which such a picture meets. The fact that the inverse power (4) which is suggested by full scaling is definitely not met by the data, which would rather favor 8, leads to the conclusion that one would be collecting events with one single $\pi^o$ with large $p_T$ as opposed to events with a group of large $p_T$ particles, one of which being the observed $\pi^o$. This may be easily connected to the type of triggering used. It is however a puzzling question that such an a priori unfavored configuration may actually dominate. In any case it would be interesting to explore other types of trigger and in particular to trigger on the overall energy in one direction rather than on one single particle. One could perhaps thus retrive a $p_T^{-4}$ term. This is however mere speculation at present.

Concluding, the study of large transverse momentum phenomena raises many exciting questions. It appears to be one of the most topical aspects of hadron physics. One may just hope that understanding the corresponding mechanisms will not lead to somewhat of a deception (unprobable but otherwise plain configurations) but rather provide new insight on the proton structure. This a hope which all results reported so far have supported.

Table I summarized the properties which define qualitatively large transverse momentum configurations as compared to well known features of particle production.

I would like to thank U. Amaldi for discussions about total cross section results and all those who participated actively in the latest ISR discussion meeting on large transverse momentum phenomena, in particular B. Blumenfeld, L. Camilieri, S. Ellis, L. Leistam and R. Thun for their important collaboration. I would also like to thank T. Cronin, H. Frisch and P. Piroué for very interesting discussions on the NAL experiment.

## TABLE I

Particle Production at Wide Angles ($x \approx 0$)

| feature | low $p_T$<br>$p_T \approx 0.3$ GeV/c | large $p_T$<br>$p_T \approx 3$ GeV/c |
|---|---|---|
| $\frac{d\sigma}{dp_T^2}$ | $e^{-6p_T}$ | $p_T^{-8}$ (?) |
| Scaling over the ISR energy range | good within 10% | wrong, rise by an order of magnitude |
| positive/negative ratio | compatible with 1 | definitely larger than 1 (1.4) |
| heavy particle/pion ratio | small (15%) | of the order of 1 |
| Associated charged multiplicity at wide angles | large positive correlations (70%) | even larger positive correlations |

## REFERENCES AND FOOTNOTES

[1] M. Jacob, A.C. Melissinos, T. Whitmore, H. Frish, Strong Interactions Annual Meeting of the APS, Chicago (1974).

[2] This does not touch the topical theme of correlations in particle production. For recent reviews see L. Foā, Rapporteur talk, Aix en Provence Conference, Supplēment au Journal de Physique 34 C-1, 317 (1973) T. Whitmore, Physics Reports, to be published and R. Slansky, Physics Reports, to be published.

[3] Evidence for a rising proton proton total cross section over the ISR energy range (250-2000 GeV, when expressed in terms of equivalent accelerator energy) was first reported by the CERN-Rome collaboration and by the Pisa Stony Brook collaboration, working independently with different techniques. The original publications are U. Amaldi et al., Phys. Letters 44B, 212 (1973) and S. R. Amendolia et al., Phys. Letters 44B, 213 (1973), respectively. For a recent review see U. Amaldi, Erice lecture notes (1973) and Rapporteur talk, Aix en Provence conference Op. Cit., 241.

Evidences for remarkable effects at large transverse momentum were first reported by the Saclay-Strasbourg collaboration [ M. Banner et al., Phys. Letters 44B, 537 (1973)], the CERN-Columbia-Rockefeller collaboration [ F. W. Büsser et al., Phys. Letters 46B , 471 (1973)] and by the British-Scandinavian collaboration [ B. Alper et al., Phys.

Letters 44B, 521, 527 (1973)] . The first results were presented at the Chicago-Batavia conference. For a recent review see J. D. Björken, Rapporteur talk, Aix en Provence Conference, Op. Cit., 385.

[4]In particular, together with more precise measurements of $\sigma$ and of the differential cross section at the ISR, one may expect results on cross sections for different channels over the NAL energy range. At the same time, new results on particle ratios at large transverse momentum and on correlations involving one large transverse momentum secondary should soon be available. This will include new data from the British-Scandinavian collaboration at ISR and the Chicago-Princeton collaboration at NAL. The CERN-Munich Streamer chamber experiment and the Saclay-Strasbourg-CERN-Columbia-Rockefeller double arm spectrometer are two new experiments which are running at present.

[5]For a survey of the situation as it looked in the spring of 1973, that is soon after the first experimental results were reported, see M. Jacob, Physics at the ISR, Fields and Quanta, to be published: Comments on Nuclear and Particle Physics 6, 71 (1973) and Comments, to be published; Ebeltoft lecture notes, CERN report 73-12 (1973).
J. D. Jackson, Scottish Universities Summer school (1973). For a survey of the situation as it looked at the time of the Aix en Provence conference see U. Amaldi and J. D. Björken, Ref. 3. The lecture notes by J. D. Jackson provide a detailed discussion of the correlated behaviour of $\sigma$, b, $\rho$ and the proton opacity.

[6] G. Belettini, Invited paper at the 5th International Conference on High Energy Collisions, Stony Brook (1973) T. Ferbel, Rochester preprint (1973).

[7] H. R. Gustafson, L. W. Jones, M. T. Longo and B. Cork, Michigan preprint (1973). These authors give $\sigma$ = 40.42 ± 0.27mb and $\sigma$ = 40.40 ± 0.28mb at 200 and 300 GeV/c respectively. This would imply a significant rise from top Serpuklov energy.

[8] See U. Amaldi - Ref. 3. The agreement between the two sets of results, which is obvious in Fig. 1 may lead to expect such a consistency.

[9] Preliminary results by this collaboration were presented at the Batavia conference. G. Giacomelli, Rapporteur talk, Proceedings of the Batavia conference.

[10] The cross section could rise for good, with the meson cloud becoming more opaque at increasing distances. As well known this may provide a rise limited to a $\log^2 S$ term (Foissart Bound). This is in particular the case in the model of Cheng and Wu, Phys. Rev. Letters 24, 1456 (1970) and in the analysis of Cheng, Walker and Wu. The rising cross section could however eventually saturate to a limiting value, as expected in Gribov Reggeon calculus in the weak coupling limit. One then expects a $(\log S)^{-1}$ approach to the limiting value of $\sigma$. See for

instance K. A. Ter Martirosyan et al., JETP Letters 11, 45 (1970) and for a review H. Abarbanel, J. Bronzan and A. White, Physics Reports, to be published.

Two points should be stressed. In the first case the coefficient of the $\log^2 S$ term observed in the data is very modest as compared to what unitarity and analyticity would allow. It is hundred times smaller! One sees therefore but a very small effect as compared to what one could expect from an asymptotic behaviour whereby an opaque proton would extend in area in the limits allowed by the finite range of strong interactions. In the second case, the limiting value which one can expect from a fit of the data is 1.5 larger than the measured value of $\sigma$. One therefore sees but a small fraction of a huge transition domain. Furthermore unless one calls for a very complicated Pomeranchon structure at 50-200 GeV, strong decreasing contributions, unexpected according to duality, would have to compensate for the rise of the diffractive part over the Serpukhov and, to some extent, NAL energy ranges. Exotic exchange could play a role there.

[11] This is in particular the case for the $K^+p$ and $p\bar{p}$ channels. The $K^+p$ channel should be very simple from the point of view of duality.

[12] See for instance the recent paper by T. K. Gaiser and G. B. Yodh, Maryland preprint (1973).

[13] V. Bartenev et al., NAL preprint (1973). A.C. Melissinos, contribution to this session.

[14] A. Martin, Proceedings of the Royal Society and CERN preprint (1973); S.M. Roy, Physics Reports (1972); S.W. MacDowell and A. Martin, Phys. Rev. 135B, 960 (1964).

[15] A value of b proportional to $\sigma$ corresponds to a fixed ratio for the elastic and total (or inelastic) cross section. Therefore the Van Hove limiting behaviour for the parameter $\sigma_{el}/\sigma_{tot}$ is practically satisfied. It keeps an almost constant value: 0.18. L. Van Hove, Rev. Mod. Phys. 36, 655 (1964).

[16] It is the relative transparency of the proton at such high energies that one may consider as the puzzling fact.

[17] It seems that assuming a purely imaginary amplitude corresponds to a good approximation. At low $|t|$, the real part is known to be small. At larger $|t|$, $|t| \sim 1.5(\mathrm{GeV/c})^2$, where the differential cross section shows a clear diffractive minimum, one can rule out a sizeable real part on the ground that its presence would have smeared out the observed structure. At intermediate $|t|$ one may find a small limit for the real part, J. Bronzan and G. Kane, private communication.

[18] R. Henzi and P. Valin, McGill preprint (1973); H. Miettinen and P. Piriula, private communication; F. Henyey et al., Michigan preprint (1973). Fig. 3 corresponds to the calculation of Miettinen and Pirula.

[19] N. N. Khuri and T. Kinoshita, Phys. Rev. 137B, 720 (1965).

[20] If the proton proton cross section rises asymptotically, the difference between the $p\bar{p}$ and pp cross sections should be such that $|\sigma_{p\bar{p}} - \sigma_{pp}| < (\sigma_{p\bar{p}} + \sigma_{pp})(\log S)^{-1}$, as shown by R. J. Eden, Phys. Rev. Letters 16, 39 (1966) and T. Kinoshita, Perspective in Modern Physics, Interscience Publ., New York (1966).

[21] One assumes for that purpose that the $p\bar{p}$ and pp cross section converge fast enough (arbitrarily small power) toward each other.

[22] J. Fisher and C. Bourrely, CERN Preprint (1973); J. Diddens and W. Bartel, CERN preprint (1973).

[23] For a review of Regge models and duality, see M. Jacob,Brandeis lecture notes (1970)

[24] I am indebted to A. White and J. Walker for a discussion of this question.

[25] Several dynamical origin for the rising cross section have been proposed. It is possible to argue for a few millibarn rise associated with a specific mechanism. It is not yet possible to show that the remainder should not decrease. This discussion was kept at a general level. For a review of some topical models see Proceedings of the Aix en Conference. U. Amaldi Rapporteur talk and R. Phillip, Summary of the parallel session on elastic scattering and low multiplicity reactions.

[26] From the SLAC results on deep inelastic electron scattering one may expect a $p_T^{-4}$ behaviour, assuming a simple factorization of the one photon exchange contribution.

[27] S. Berman, I. Bjorken and T. Kogut, Phys. Rev. D4, 3388 (1971); T. Kogut and D. Susskind, Physics Reports 8C (73).

[28] S. Berman and M. Jacob, Phys. Rev. Letters 25, 1683 (70).

[29] This was a deception for lepton searches conducted beyond the commonly produced pions. It was an unexpected bonus for hadron physics at the ISR.

[30] Large transverse momentum phenomena ISR Discussion meeting -7 CERN internal report (1973).

[31] B. G. Pope, Aix Proceedings Op. Cit., 407, L. J. Caroll, 409.

[32] D. Theriot, Aix Proceedings Op. Cit., 415.

[33] J. Cronin, Aix Proceedings 418; J. Cronin et al., Phys. Rev. Letters 31, 1426 (1973).

[34] H. J. Frisch, contribution to this session; New results at 400 GeV/c are also presented; They confirm all trends seen on the 200 and 300 GeV data put together.

[35] G. Jarlskog, contribution to the Marseille meeting on hadron interactions at ISR energies (1973).

[36]This is related to the well known fact that fits such as (4) gives smaller values for B for K and $\bar{p}$.

[37]Rather than stressing thus a drop of the $p/\pi^+$ ratio, one should emphasize the fact that the pion yield rises, as well as others, and much more than the proton yield does.

[38]One may consider very large multiplicity reactions giving slow protons at large $p_T$. Their proton yield at $x = 0$ would decrease with energy.

[39]J. D. Björken, Proceedings of the Aix en Provence conference, Ref. 3, J. C. Potkinghorne,ibid., p. 421 and references therein, S. Ellis, Ref. 30.

[40]S. Ellis and M. Kisslinger, NAL preprint (1973).

[41]S. Brodsky, R. Blankenbecler and F. Gunion. SLAC preprints (1973).

[42]See H. Frish in Ref. 34. What is more important is that the scaling function G, as determined from the NAL data, would appear as going to zero at large energy as opposed to the finite value suggested by the ISR results.

[43]It should be worthwhile to explore in more detailed $p_T$ bias on the trigger used by the CCR experiment (a large $p_T$ pion implies yields at large rapidity which are below average) and nuclear corrections to the very small cross sections seen in the CP experiment. The

region of $x_T$ where the CP experiment fits most strigently (6) is above that used by CCR. One may not then mention any disagreement. Non asymptotic mass effects could still be important and contribute to the discrepancy. I am much indebted to J. Cronin, H. Frish, R. Blankenbeder and G. Farrar for discussions on this point.

[44] They confirm and extend results reported previously. See ISR discussion meetings 4 and 7 (1973). I am indebted to R. Thun for several discussions on this question.

[45] As already mentioned the CERN-Munich Streamer chamber with a trigger on a large transverse momentum $\pi^\circ$ should soon give most interesting results. This should also be the case of the Saclay-Strasbourg double arm spectrometer at 90°, used together with the CERN-Columbia-Rockefeller lead glass detector. NAL experiments with incident pions should give specifically different charge ratios if the effect is to be associated with hard parton constituents.

[46] The "Identity-kit portrait" of a large $p_T$ reaction, as so far triggered upon, gives a large momentum $\pi^\circ$ at rapidity zero together with one or two soft pions above average, within two units of rapidity around zero in the hemisphere centered on the triggering direction. In the opposite hemisphere the number of soft pions increase almost linearly with $p_T$ to reach 3 to 4 above average at $p_T = 4\mathrm{GeV}/c$, again within two units of rapidity around zero. On top of this one or two larger $p_T$ secondaries stand out on that side. The overall picture should rotate when one rotates the direction of the triggering pion. The associated multiplicity becomes skewed while remaining large at $y = 0$.

## FIGURE CAPTIONS

Fig. 1 The proton proton total cross section.

Fig. 2 The slope parameter of the elastic proton proton differential cross section. It is defined for $|t| < 0.1(\text{GeV}/c)^2$.

Fig. 3 The impact parameter differential inelastic cross section as inferred from the differential elastic cross section. Its vanishing at $r = 0$ is an obvious Jacobian effect. Also shown is the rise of the inelastic cross section which is small as compared to what it could be if limited by unitarity only. It is rather confined to a peripheral region.

Fig. 4 The ratio of the real to the imaginary part of the proton proton elastic forward amplitude. It follows predictions from dispersion relations using a rising pp cross section and pp and $p\bar{p}$ cross sections approaching each other.

Fig. 5 The inclusive distribution observed by the Saclay-Strasbourg collaboration for positives ($p_T < 3\text{GeV}/c$) and pions ($p_T > 3\text{GeV}/c$) at $x = 0$ and $\sqrt{S} = 53\text{GeV}$. Also shown is the energy behaviour of the integrated pion yield between $p_T = 3.2$ and $5.2\text{GeV}/c$. The observed rise agrees with that observed by the CERN-Columbia-Rockefeller collaboration for $\pi^\circ$ . Agreement on the trend is more important than the overall normalization discrepancy.

Fig. 6 — The inclusive $\pi^\circ$ distribution observed by the CERN-Columbia-Rockefeller collaboration at $x = 0$ as a function of energy. It shows a strong energy dependence which could however lead to a belated scaling property, with eventually an inverse power $p_T$ dependence. The solid line corresponds to the extrapolation of the energy independent low $p_T$ results.

Fig. 7-a — The relative amount of pions, kaons and proton (and anti proton) as a function of $p_T$ . Data are from the British-Scandinavian collaboration ($x = 0$, $\sqrt{S} = 53\text{GeV}$).

Fig. 7-b — The $\pi^+/\pi^-$ , $p/\bar{p}$ and $p/\pi^+$ ratios as a function of $p_T$. The $k^+/k^-$ ratio is very close to the $\pi^+/\pi^-$ ratio.

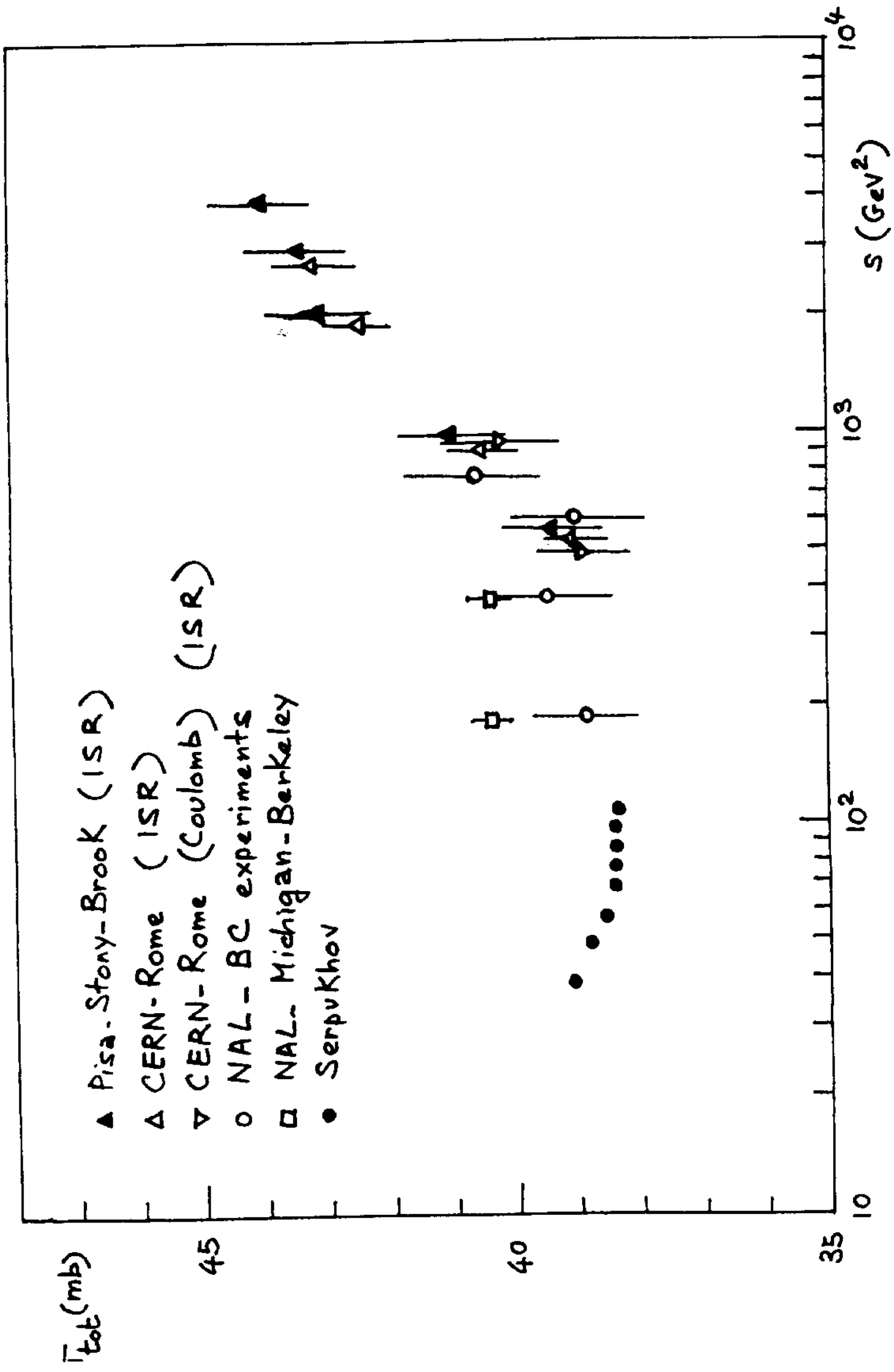
Fig. 7-c — The $p/\pi^+$ , $k^+/\pi^+$ , $k^-/\pi^-$ and $\bar{p}/\pi^-$ ratios as functions of $p_T$ at $x \approx 0$ , $\sqrt{S} = 23\text{GeV}$. The large $p_T$ data are from the Chicago-Princeton collaboration at NAL. The low $p_T$ data are from the British-Scandinavian collaboration at the ISR.

Fig. 8 Evidence for a scaling behaviour of $p_T^N \frac{d\sigma}{dp_T^2}$, as obtained for $\pi^\circ$ inclusive distributions at $x = 0$ measured by the CERN-Columbia-Rockefeller collaboration.

Fig. 9-a Associated charged multiplicity to a large $p_T$ $\pi^\circ$, as a function of $p_T$. On the left side, the multiplicity is that observed in a relatively small solid angle (1.1 sr) in the direction of the observed $\pi^\circ$. On the right side, it is that observed in the opposite direction. Results are normalized to the average yield from inelastic events. Data are from the CERN-Columbia-Rockefeller collaboration.

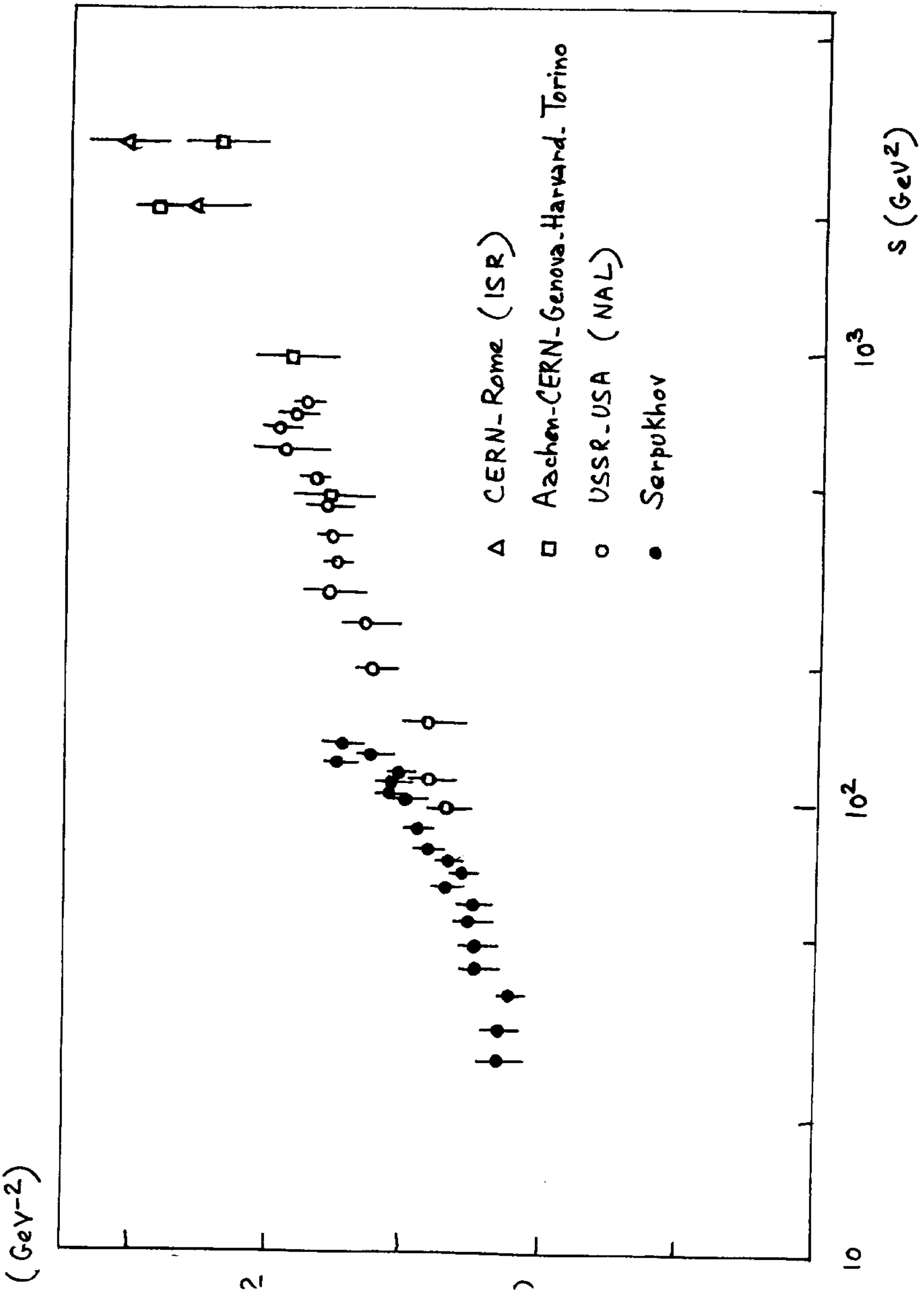
Fig. 9-b Azimuthal distribution of the associated charged multiplicity to a large $p_T$ $\pi^\circ$. The distributions are integrated over the rapidity interval $-0.8 < \eta < 0.8$ where most of the positive correlations are found. The direction of the $\pi^\circ$ corresponds to $|\phi| < 15^\circ$. Data are from the Pisa Stony Brook collaboration. The yields are normalized to average inelastic events.

figure 1



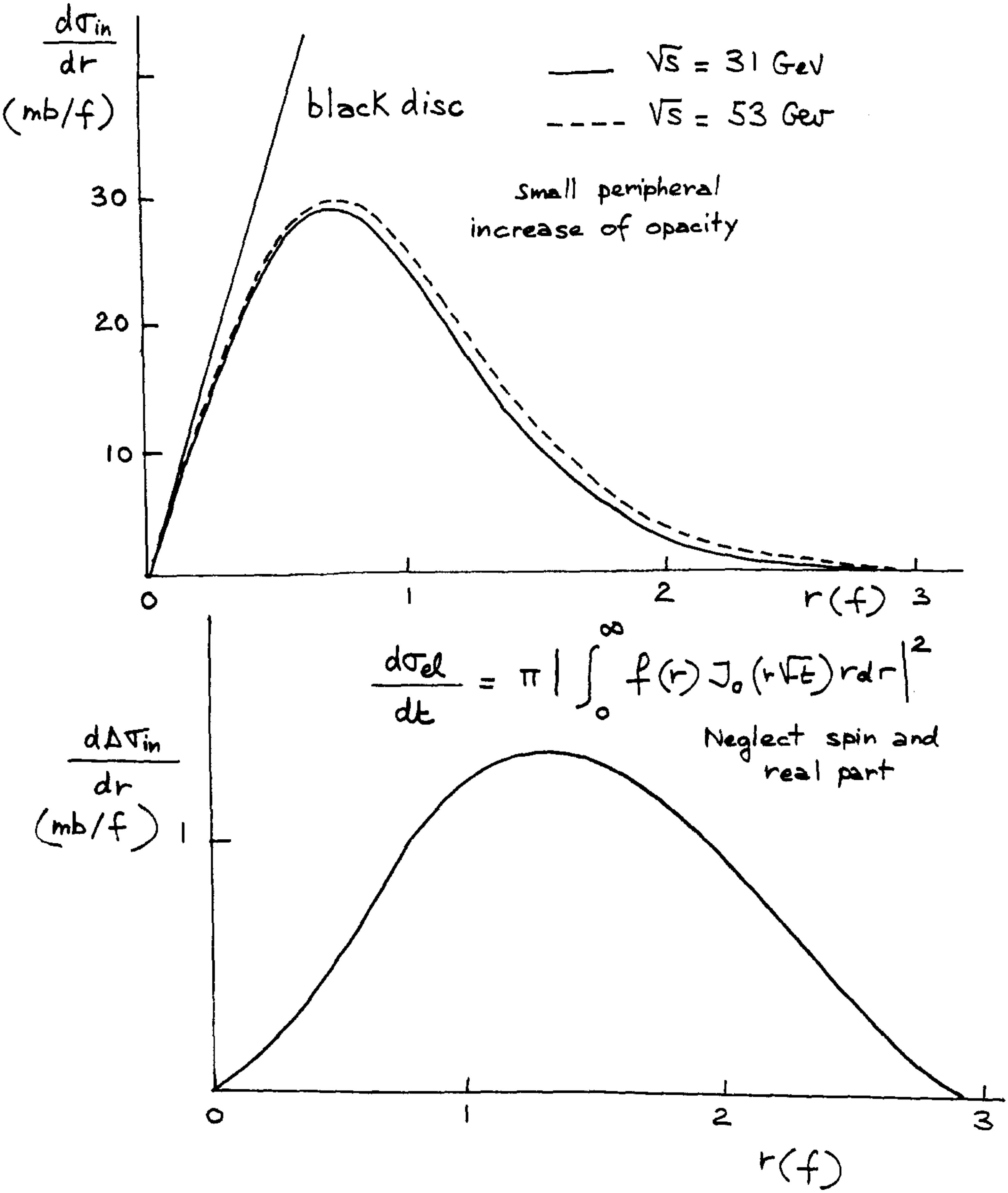
$\sigma_{tot}$ (mb)
45
40
35
10
$10^2$
$10^3$
$10^4$
s (GeV$^2$)
▲ Pisa - Stony - Brook (ISR)
△ CERN - Rome (ISR)
▽ CERN - Rome (Coulomb) (ISR)
○ NAL - BC experiments
□ NAL - Michigan - Berkeley
● Serpukhov

figure 2



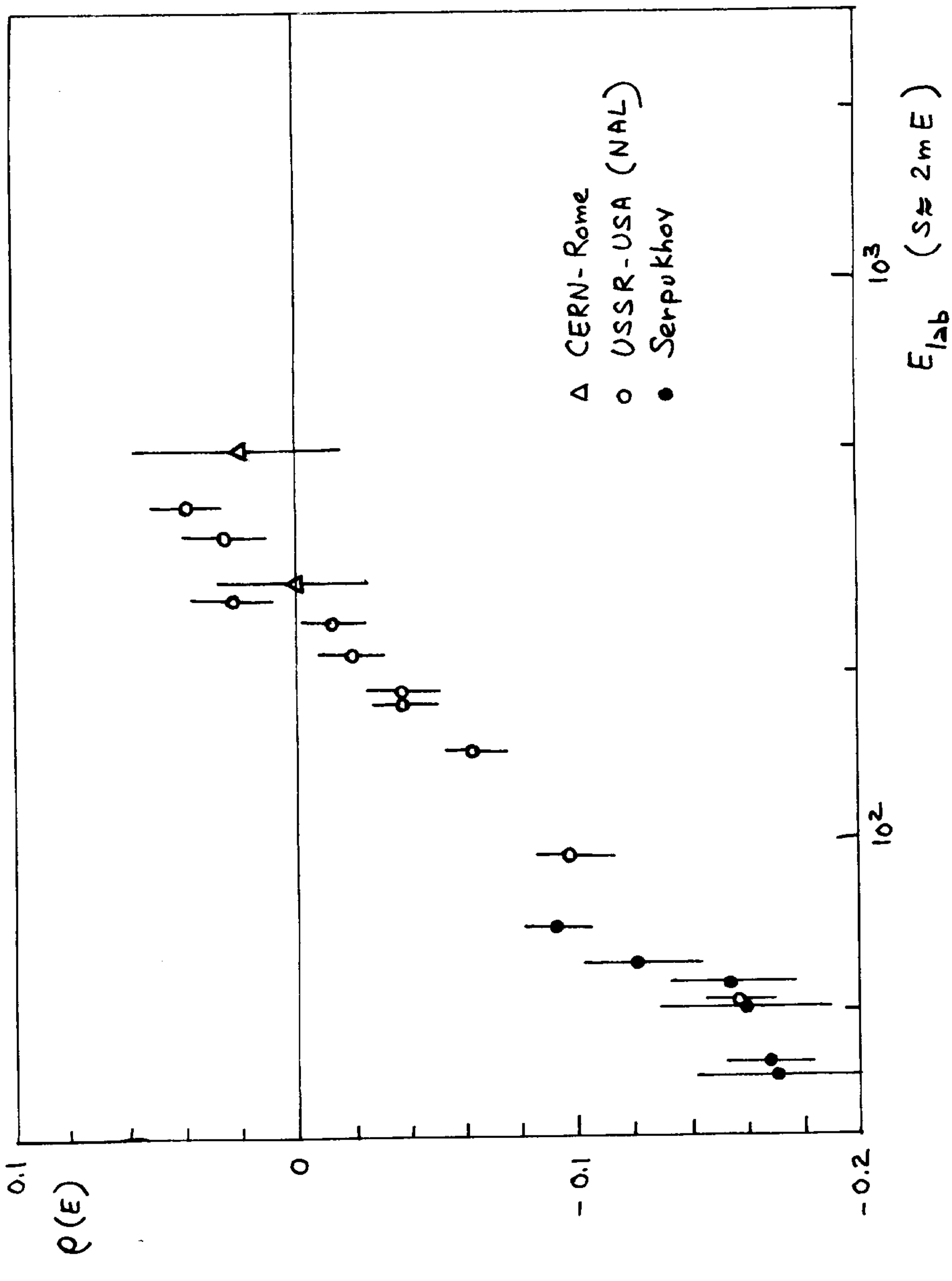
CERN-Rome (ISR)
Aachen-CERN-Genova-Harvard-Torino
USSR-USA (NAL)
Serpukhov
s (GeV$^2$)
10
$10^2$
$10^3$
(GeV$^{-2}$)
2
0

figure 3



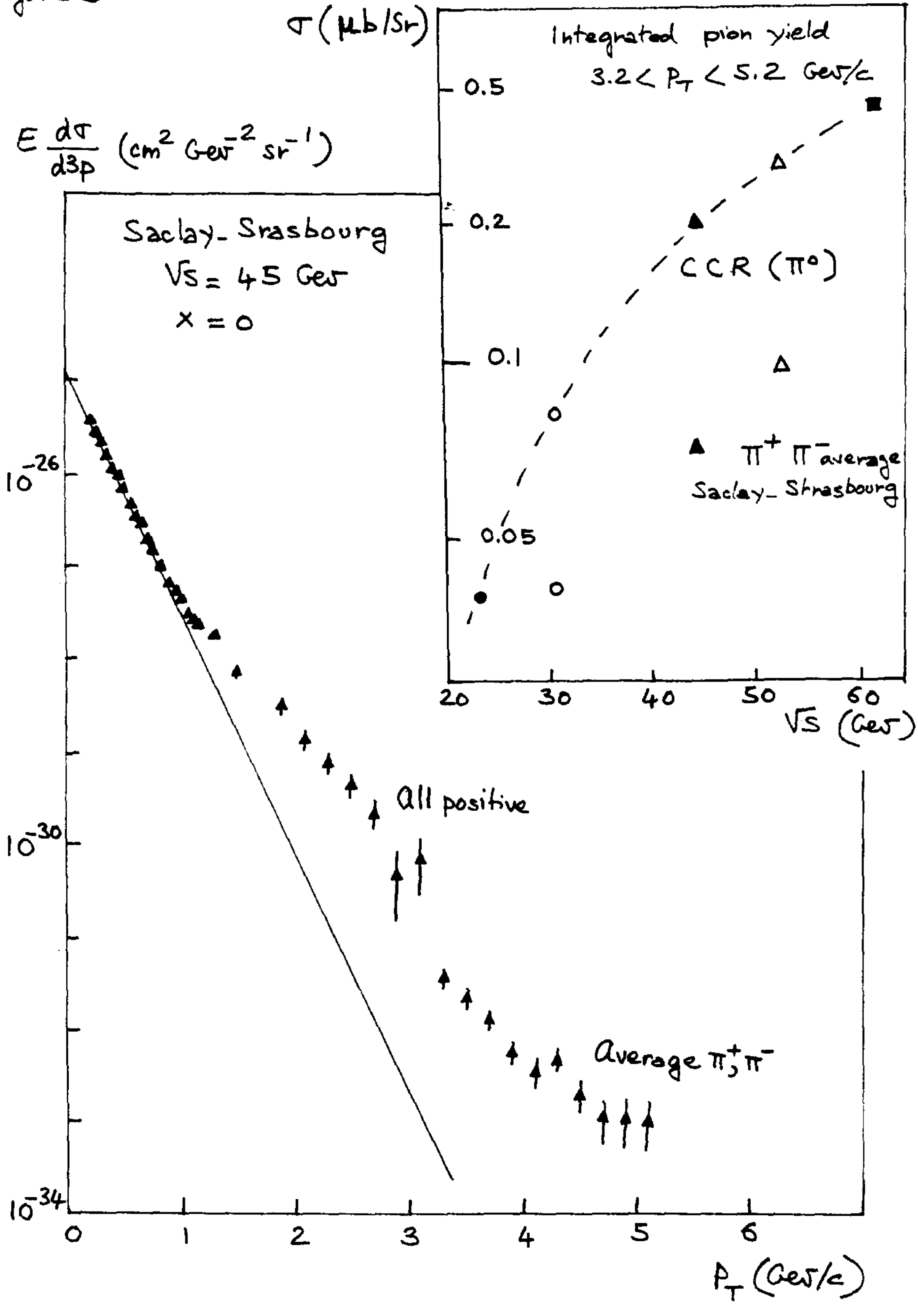
$\frac{d\sigma_{in}}{dr}$ (mb/f)
30
20
10
0
1
2
r(f) 3
black disc
$\sqrt{s}$ = 31 GeV
$\sqrt{s}$ = 53 GeV
small peripheral increase of opacity
$\frac{d\sigma_{el}}{dt} = \pi \left| \int_0^\infty f(r) J_0(r\sqrt{t}) r dr \right|^2$
Neglect spin and real part
$\frac{d\Delta\sigma_{in}}{dr}$ (mb/f)
1
0
1
2
3
r(f)

figure 4



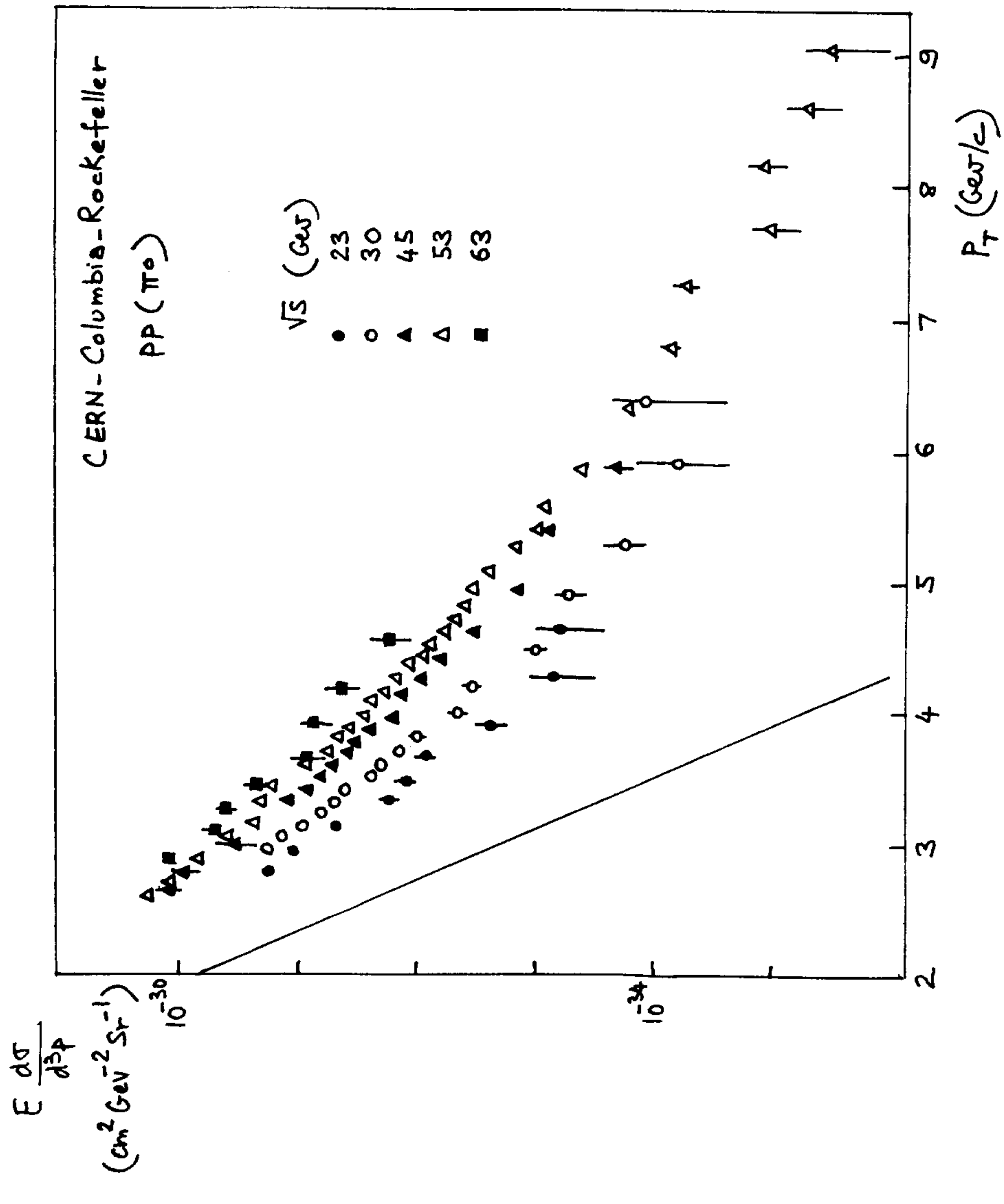
Δ CERN-Rome
○ USSR-USA (NAL)
● Serpukhov
0.1
0
-0.1
-0.2
ρ(E)
$10^2$
$10^3$
$E_{lab}$ (s ≈ 2mE)

figure 5



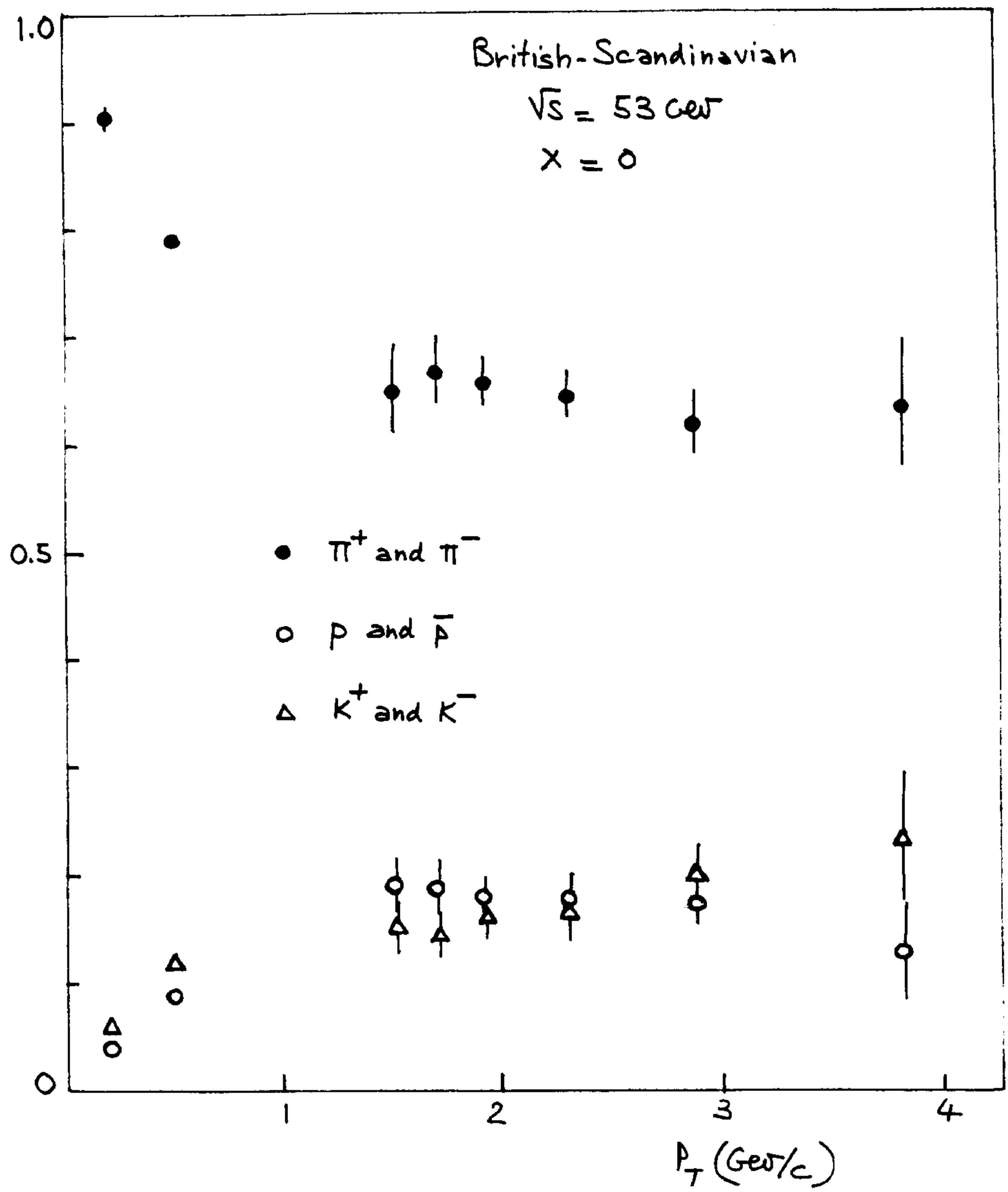
σ (μb/Sr)
Integrated pion yield
3.2 < $P_T$ < 5.2 GeV/c
0.5
0.2
0.1
0.05
CCR (π°)
π⁺ π⁻ average
Saclay-Strasbourg
20
30
40
50
60
√s (GeV)
E dσ/d3p (cm² GeV⁻² sr⁻¹)
Saclay-Srasbourg
√s = 45 GeV
x = 0
10⁻²⁶
10⁻³⁰
10⁻³⁴
All positive
Average π⁺, π⁻
0
1
2
3
4
5
6
$P_T$ (GeV/c)

figure 6



CERN - Columbia - Rockefeller
pp (π°)
√s (GeV)
23
30
45
53
63
P_T (GeV/c)
2
3
4
5
6
7
8
9
10^-30
10^-34
E dσ/d³p
(cm² GeV⁻² Sr⁻¹)

figure 7-a



British-Scandinavian
$\sqrt{s} = 53$ GeV
$X = 0$
$\pi^+$ and $\pi^-$
p and $\bar{p}$
$K^+$ and $K^-$
1.0
0.5
0
1
2
3
4
$P_T$ (GeV/c)

figure 7 b

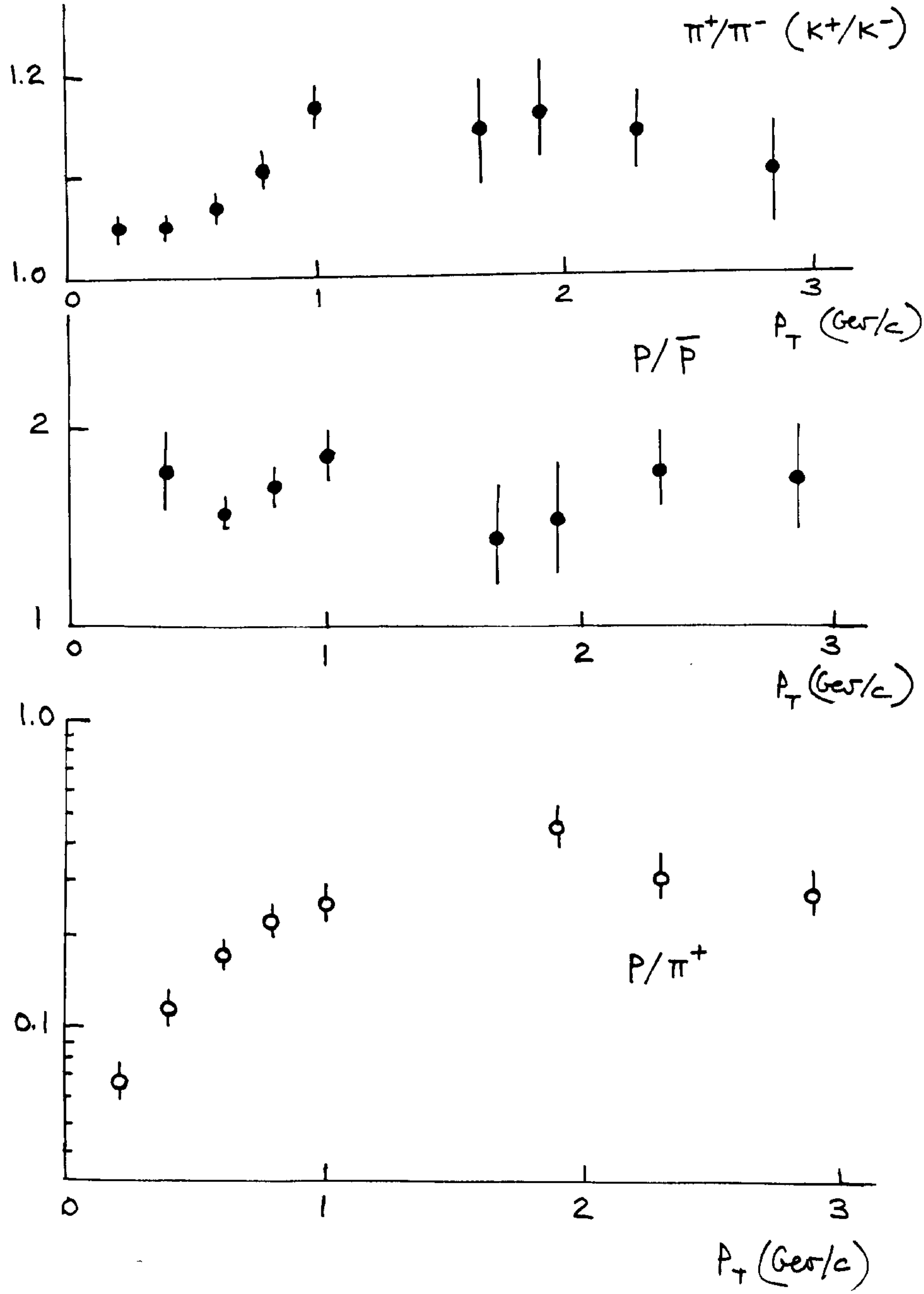
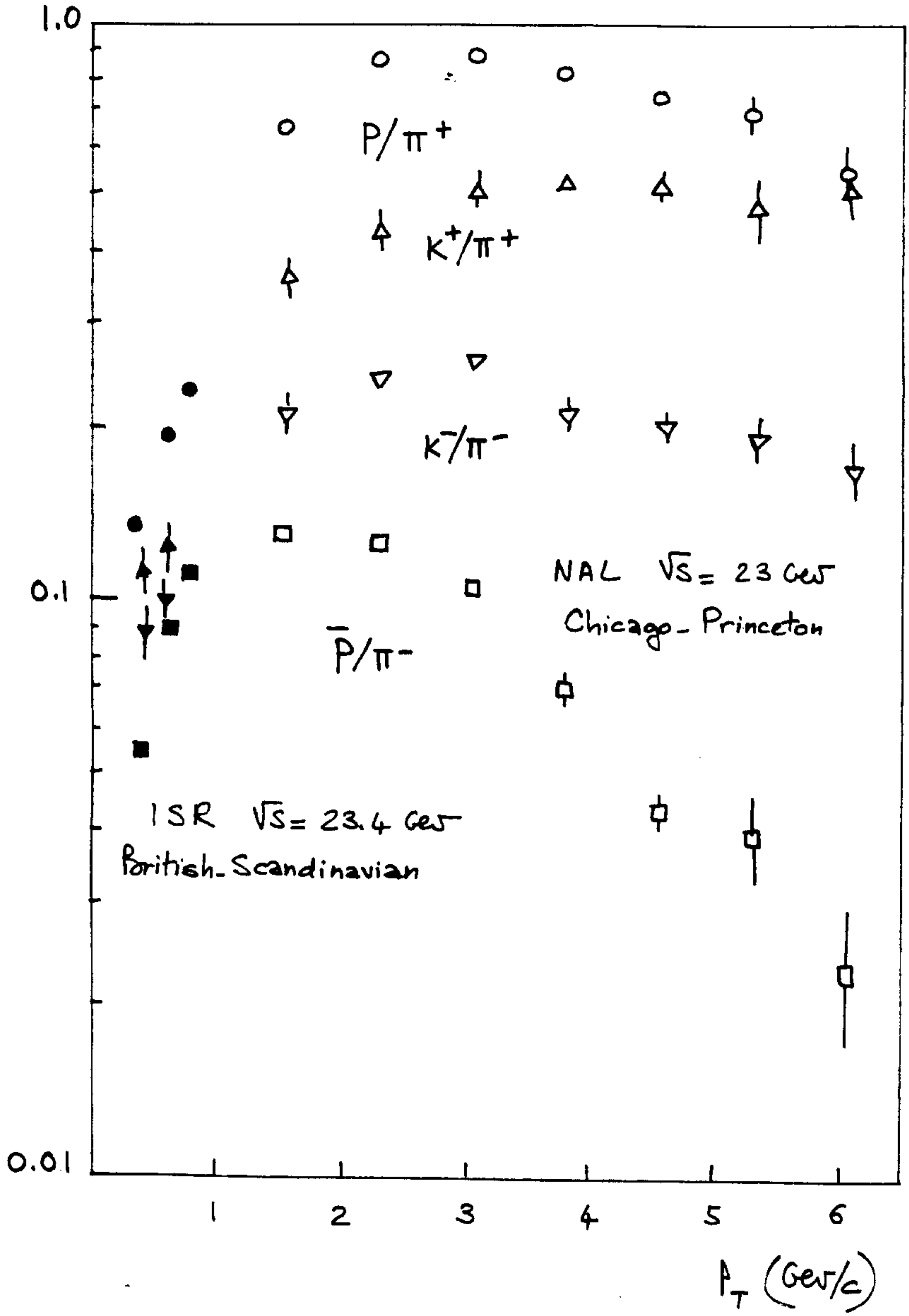
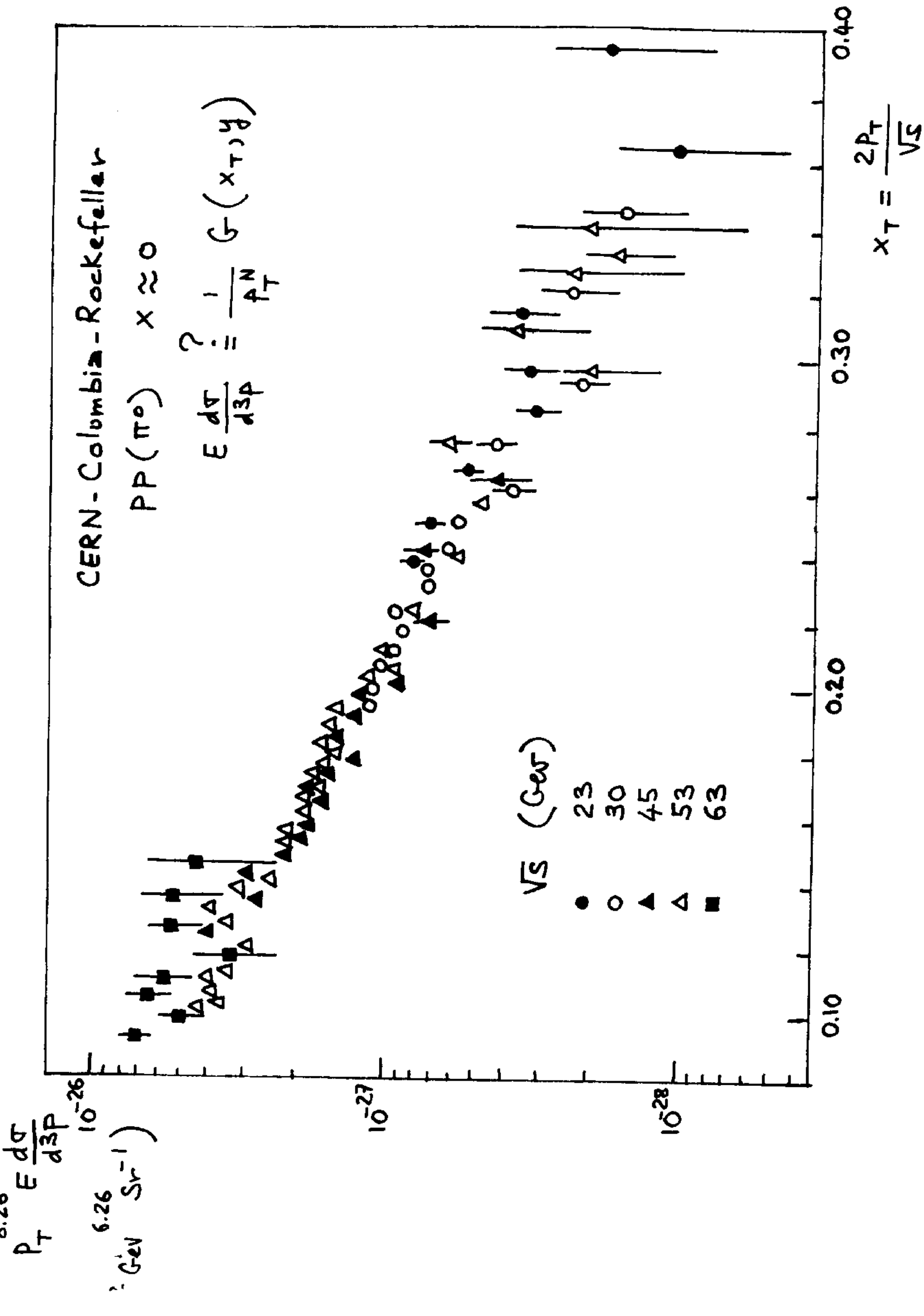


figure 7-c



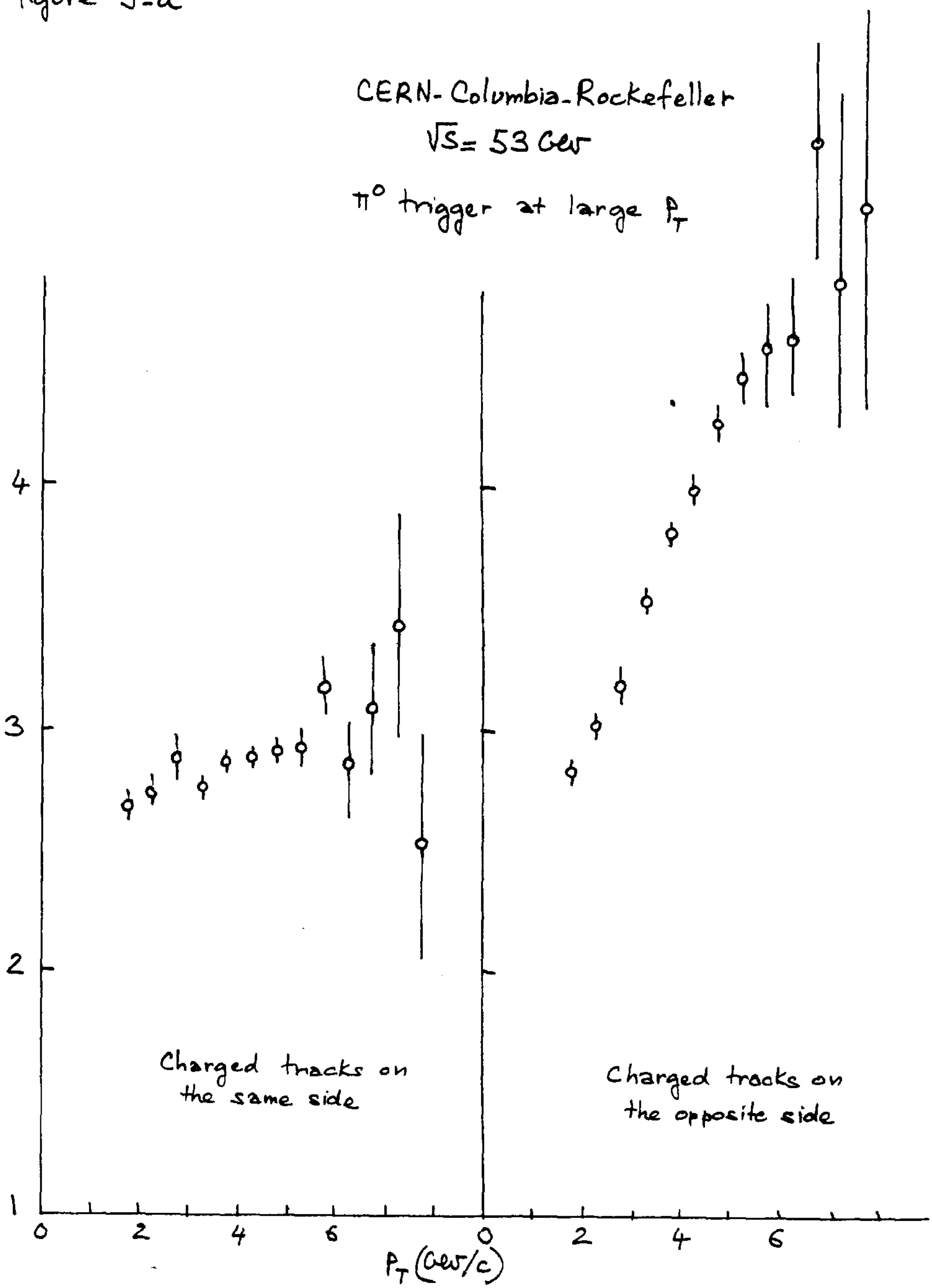
1.0
0.1
0.01
$P/\pi^+$
$K^+/\pi^+$
$K^-/\pi^-$
$\bar{P}/\pi^-$
NAL √s = 23 GeV
Chicago-Princeton
ISR √s = 23.4 GeV
British-Scandinavian
1
2
3
4
5
6
$p_T$ (GeV/c)

figure 8



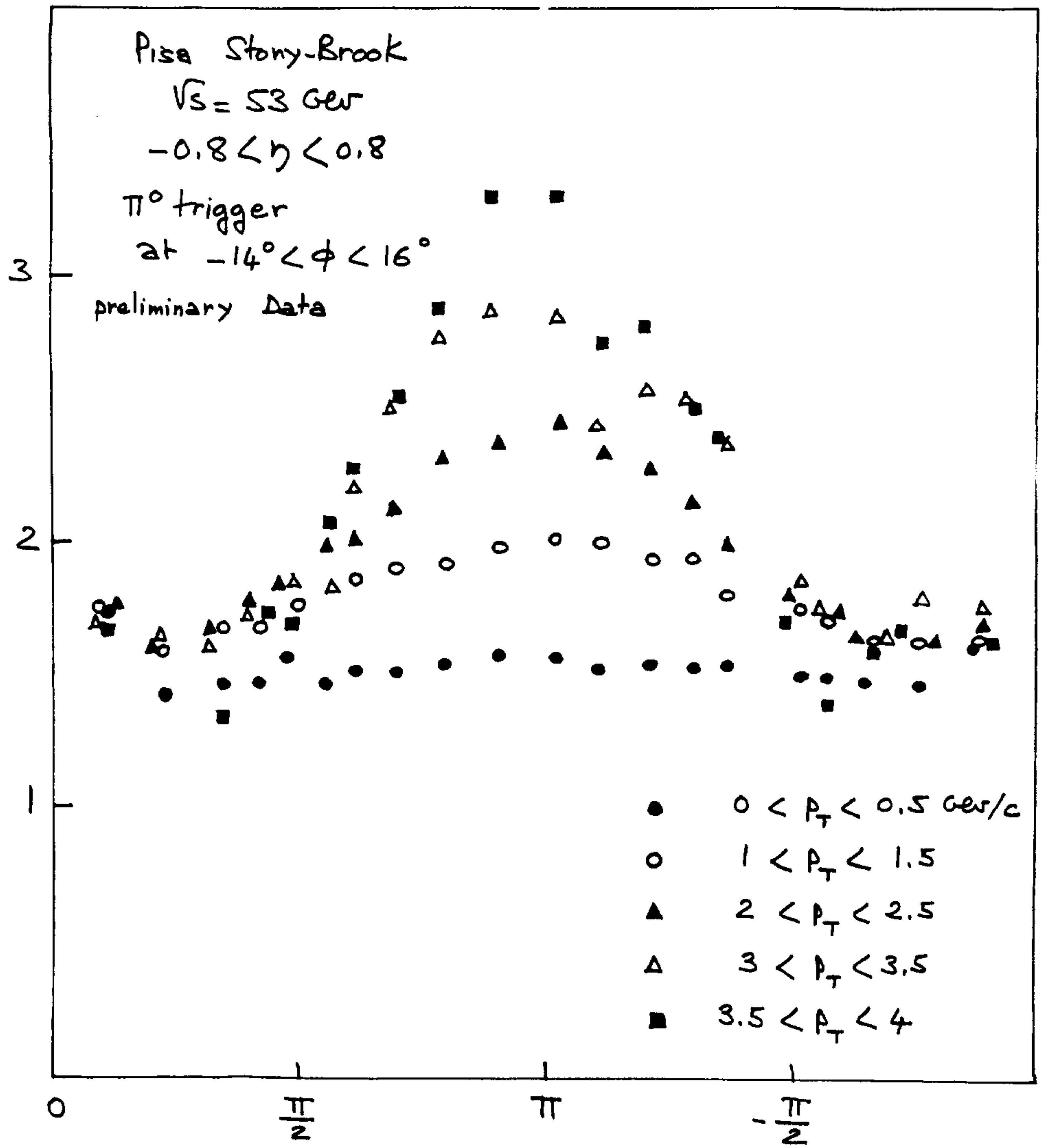
CERN - Columbia - Rockefeller
PP ($\pi^0$) $x \approx 0$
$E\frac{d\sigma}{d^3p} \stackrel{?}{=} \frac{1}{p_T^N} G(x_T, y)$
$\sqrt{s}$ (GeV)
23
30
45
53
63
$p_T^{8.26} E\frac{d\sigma}{d^3p}$
$(GeV^{6.26}\ Sr^{-1})$
$10^{-26}$
$10^{-27}$
$10^{-28}$
0.10
0.20
0.30
0.40
$x_T = \frac{2p_T}{\sqrt{s}}$

Figure 9-a



CERN-Columbia-Rockefeller
√s = 53 GeV
π⁰ trigger at large $p_T$
4
3
2
1
Charged tracks on the same side
Charged tracks on the opposite side
0
2
4
6
0
2
4
6
$p_T$ (GeV/c)

figure 9_b



Pisa Stony-Brook
$\sqrt{s} = 53$ GeV
$-0.8 < \eta < 0.8$
$\pi^0$ trigger
at $-14° < \phi < 16°$
preliminary Data
3
2
1
0
$\frac{\pi}{2}$
$\pi$
$-\frac{\pi}{2}$
$0 < p_T < 0.5$ GeV/c
$1 < p_T < 1.5$
$2 < p_T < 2.5$
$3 < p_T < 3.5$
$3.5 < p_T < 4$